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MODEL ATMOSPHERE ANALYSES OF ULTRAVIOLET SPECTRA OF NOVAE IN OUTBURST

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The Physics of Early Nova Spectra

with S. Shore, F. Allard, and E. Baron

We discuss the physical effects that are important for the formation of the early spectra of novae. Nova atmospheres are optically thick, fast expanding shells with flat density profiles, leading to geometrically very extended atmospheres. We show that the properties of early nova spectra can be understood in terms of this basic model and discuss some important effects that influence the structure and the emitted spectrum of nova atmospheres, e.g., line blanketing, NLTE effects, and the velocity field. The proper modeling of nova atmospheres is discussed and we give some computational details.

Non-LTE Treatment of Fe IIin Astrophysical Plasmas

with E. Baron

We describe our implementation of an extremely detailed model atom of singly ionized iron for NLTE computations in static and moving astrophysical plasmas. Our model atom includes 617 levels, 13675 primary permitted transitions and up to 1.2 million secondary transitions. Our approach guarantees that the total iron opacity is included at the correct wavelength with reasonable memory and CPU requirements. We find that the lines saturate the wavelength space, such that special wavelength points inserted along the detailed profile functions may be replaced with a statistical sampling method. We describe the results of various test calculations for novae and supernovae.

The early evolution of Nova Cas 1993

with S. Shore, G. Sonneborn and F. Allard

We discuss the evolution of the bright nova Cas 1993 over the first two months after its discovery. We use synthetic spectra to interpret the both low-resolution SWP & LWP as well as high-resolution LWP spectra. Our models show that the effective temperature of the atmosphere of Cas 93 increased from $\approx 8000\,\mathrm{K}$ to about $\approx 16,000\,\mathrm{K}$ from Dec. 12, 1993 to Dec. 26, 1993 and afterwards increased slowly to reach about 24,000 at Jan. 28, 1994. A preliminary abundance analysis shows evidence for hydrogen depletion as in nova Cygni 1992 but in addition suggest a much higher overabundance of carbon, nitrogen and oxygen. We discuss, in addition, the possiblity of a radiatively driven wind ejection by Cas 1993.

Some Remarks About Nova Spectroscopy And Photometry

with S. Pistinner and G. Shaviv

We explore the proper parameterization of a novae envelopes. Numerical results show that certain regions of the continuum spectra are not sensitive to the input parameters.

We establish that in certain cases nova atmospheres have a continuum extinction coefficient that is dominated by scattering. The continuum scattering and the resulting continuum extinction in these cases are nearly gray. We apply and extend the small parameter Chandrasekhar expansion and use the particular properties of the opacity to study the effect of small absorption in the atmosphere. Two cases are treated, the case of a static extended atmosphere, and the case of an extended atmosphere in motion. We solve the transfer equation under the above physical conditions self consistently. The assumption of radiative equilibrium allows us to obtain a self consistent temperature profile to validate our approximation a *posteriori*.

Using this solutions, we a) derive conditions for the required magnitude accuracy and the required observed frequency range needed to obtain a prescribed accuracy of a nova parameters from comparison of spectra to models. b) assess and establish the importance of spectroscopic (in contrast to photometric) measurements. c) show that the use of synthetic spectra calculations are an essential part of any determination of nova characteristics from the observations performed in the photospheric phase. We find that the only wavelength region which is not affected by the physical conditions that were used to arrive at these conclusions is the UV. Therefore, we conclude that the UV serves as *the* wavelength region to derive nova parameters in a robust manner, when synthetic spectral techniques are used.

Model Atmospheres for M (Sub)Dwarf stars: I. The base model grid

with France Allard

We have calculated a grid of more than 700 model atmospheres valid for a wide range of parameters encompassing the coolest known M dwarfs, M subdwarfs and brown dwarf candidates: $1500 \leq T_{\rm eff} \leq 4000\,{\rm K}$, $3.5 \leq \log(g) \leq 5.5$, and $-4.0 \leq [M/H] \leq +0.5$.

Our equation of state includes 105 molecules and up to 27 ionization stages of 39 elements. In the calculations of the base grid of model atmospheres presented here, we include over 300 molecular bands of 4 molecules (TiO, VO, CaH, FeH) in the JOLA approximation, the water opacity of Ludwig (1971), collision induced opacities, b-f and f-f atomic processes, as well as about 2 million spectral lines selected from a list with more than 42 million atomic and 24 million molecular (H_2, CH, NH, OH, MgH, SiH, C_2, CN, CO, SiO) lines. High-resolution synthetic spectra are obtained using an opacity sampling method. The model atmospheres and spectra are calculated with the generalized stellar atmosphere code `PHOENIX`, assuming LTE, plane-parallel geometry, energy (radiative plus convective) conservation, and hydrostatic equilibrium.

The model spectra give close agreement with observations of M dwarfs across a wide spectral range from the blue to the near-IR, with one notable exception: the fit to the water bands. We discuss several practical applications of our model grid, e.g., broadband colors derived from the synthetic spectra. In light of current efforts to identify genuine brown dwarfs, we also show how low-resolution spectra of cool dwarfs vary with surface gravity, and how the high-resolution line profile of the Li I resonance doublet depends on the Li abundance.

Water vapor in the spectra of cool stars

with H. Jones et al.

We present comparisons between observed and synthetic spectra for water vapor transitions in a range of M dwarfs. The observations were from 2.85–3.40 μm where water vapor transitions are strong in cool stars but relatively weak in the Earth's atmosphere allowing reliable observations to be made. They illustrate the strength of water vapor in cool dwarfs and prove the ability of the current generation of infrared array spectrometers to take high quality spectra in this little used spectral region. The synthetic spectra were computed using PHOENIX and include preliminary ab initio calculations for ro-vibrational bands arising from water vapor transitions from levels up to J=30 above the ground state. Although the molecular opacity in the region of comparison is accurate, it is not around the peak of the flux distribution and so the uncertainties of a reliable model atmosphere structure and an absolute temperature scale still remain. Both the observed and synthetic spectra are strongly sensitive to temperature. We find that within the calculational uncertainties the predicted strengths and positions of the water transitions accord with the observations.

Infrared spectra of low–mass stars: towards a temperature scale for red dwarfs

with S. Leggett et al

We present new low–resolution (R$\sim$ 250) 1.0—2.4μm spectra for 13 red dwarf stars. The sample size is increased to 16 by including other published infrared spectra. New, as well as published, red spectra are presented for 10 of these 16 stars, and new and published VRIJHKLL$'$ photometry is also presented. Both halo and disk stars are included in the sample, which covers a range of spectral type from dM0 to dM6.5. We derive bolometric luminosities and bolometric corrections from the observational data, finding good agreement with earlier results for the disk stars. We fit synthetic spectra generated by Allard & Hauschildt's model atmospheres to the observed spectra. Although some discrepancies remain between the theoretical and observed spectra we find that the molecular features give a consistent value for effective temperature across the entire observed wavelength range. The $T_{\rm eff}$'s and radii derived are in good agreement with structural models of low–mass stars. This removes a long–standing discrepancy between the observed and calculated locations of such stars in the HR diagram, for stars more massive than 0.1 $M_\odot$.

New evolutionary tracks for very-low-mass stars

with I. Baraffe, G. Chabrier, and F. Allard

We present new evolutionary calculations for low-mass and very low-mass M-dwarfs, for a metallicity range $-2 \leq [M/H] \leq 0$, down to the hydrogen-burning minimum mass ($0.07 < M/\,M_\odot < 0.6$). The calculations include the best input physics presently available, i.e. equation of state, enhancement of nuclear reaction rates and atmosphere models. We use the most recent atmosphere models calculated by Allard and Hauschildt (1994), based on *synthetic* spectra at finite metallicity , and grey atmosphere models based on Alexander and Fergusson (1994) Rosseland opacities. Comparisons are made with observational results down to the bottom of the main sequence, for different metallicities, in a magnitude (M_V) - color ($V-I$) diagram, and in color-color I, J, H, K diagrams. We find an excellent agreement between theory and observations over the whole characteristic temperature/luminosity range. This enables us to determine the mass of the faintest

objects observed, which is found to be $m_{lim} \approx 0.085\,M_\odot$ for [M/H]=0 and -0.5, and $m_{lim} = 0.09\,M_\odot$ for [M/H]=-1.5, for an age of 10 Gyrs.

CONVERGENCE PROPERTIES OF THE ACCELERATED Λ-ITERATION

with H. Störzer and E. Baron

We investigate the convergence properties and the computational speed of the accelerated Λ-iteration method for the solution of a wide variety of radiative transfer problems. The formal solution of the transfer equation is done using the short characteristics method. As the approximate Λ-operator we use bands of the discretized Λ-operator and derive the formulae for computing operators with arbitrary bandwidth.

We define the optimum bandwidth of the approximate Λ-operator as the bandwidth for which the CPU time used for the solution of any particular radiative transfer problems is minimum. The radiative transfer equation is solved for a number of continuum and line transfer problems in spherical symmetry and for static to very rapidly expanding media. We find the optimum bandwidth is around 5–15 for workstation class computers whereas it is around 1–2 for supercomputers.

NLTE effects on the strength of the Lyman edge in Quasar accretion disks

with H. Störzer

We have calculated far ultraviolet (FUV, 300 Å$\leq \lambda \leq$ 1500 Å) continuous energy distributions of accretion disks in the centers of active galactic nuclei (AGNs) for disk luminosities in the range $0.1 \cdot L_{\rm Edd} \leq L_{\rm acc} \leq 1.0 \cdot L_{\rm Edd}$ and central masses ranging from $10^8 M_\odot$ to $10^{10} M_\odot$. The vertical gas pressure structure of the disk and the disk height is obtained analytically, the temperature stratification and the resulting continuum radiation fields are calculated numerically. We have included NLTE effects both of the ionization equilibrium and the level populations of hydrogen, helium, magnesium and calcium. We show that these NLTE effects reduce the strength of the Lyman edge when compared to the LTE case. In NLTE we find that the edge can be in emission or absorption, depending on the disk parameters.

NLTE Model Atmospheres for M Dwarfs and Giants

with F. Allard, D.R. Alexander, A. Schweitzer, E. Baron

The atmospheres of M stars are dominated by a small number of very strong molecular compounds (H_2O, TiO, H_2, CO, VO). Most of the hydrogen is locked in molecular H_2, most of the carbon in CO; and H_2O, TiO and VO opacities define a pseudo-continuum covering the entire flux distribution of these stars. The optical "continuum" is due to TiO vibrational bands which are often used as temperature indicators for these stars. These may be the depth of the bands relative to the troughs in between them; or the depth of the VO bands; or of the atomic lines relative to the local "continuum"; or even the strength of the infrared water bands; all of these depend on the strength of the TiO bands and the amount of flux-redistribution to longer wavelengths exerted by them. Departures from LTE of the Ti I atom, and thus the concentration of the important TiO molecule,

could, therefore, have severe and measurable consequences on the atmospheric structure and spectra of these stars.

Due to the very low electron temperatures, the electron density is extremely low in M stars; even lower than in novae and SNe. Collisions with particles other than electrons, e.g., the H_2 or helium, are by far not as effective as electron collisions, both because of their smaller cross-sections and of their much smaller relative velocities. Therefore, collisional rates which tend to restore LTE, could be very small in cool stars. This in turn could significantly increase the importance of NLTE effects in M stars when compared to, e.g., solar type stars.

In this paper we discuss NLTE effects of Ti I in fully self-consistent models for a few representative M/Brown dwarf and M giant model atmospheres and spectra.

Spectrum Synthesis of the Type Ia SNe

with E. Baron, P. Nugent, D. Branch

We present NLTE synthetic spectra for the Type Ia supernovae SN 1992A SN 1981B, and SN 1991bg near maximum light. At this epoch both of the normal SNe Ia (SNe 1981b and 1992A) were observed from the UV through the optical. This wide spectral coverage is essential for determining the density structure of a SN Ia. Our fits are in good agreement with observation and provide some insight as to the differences between these supernovae. We show that SNe Ia form a spectral sequence which can be understood in terms of their luminosity. We also discuss the application of the spectral fitting expanding atmosphere method (SEAM) to SNe Ia which gives a distance that is independent of those based on the decay of ^{56}Ni and Cepheid variable stars.

The Effects of Fe II NLTE on Nova Atmospheres and Spectra

Peter H. Hauschildt, E. Baron, S. Starrfield, F. Allard

The atmospheres of novae at early times in their outbursts are very extended, expanding shells with low densities. Models of these atmospheres show that NLTE effects are very important and must be included in realistic calculations. We have, therefore, been improving our atmospheric studies by increasing the number of ions treated in NLTE. One of the most important ions is Fe II which has a complex structure and numerous lines in the observable spectrum. In this paper we investigate NLTE effects for Fe II for a wide variety of parameters. We use a detailed Fe II model atom with 617 level and 13675 primary lines, treated using a rate-operator formalism. We show that the radiative transfer equation in nova atmospheres *must* be treated with sophisticated numerical methods and that simple approximations, such as the Sobolev method, *cannot* be used because of the large number of overlapping lines in the co-moving frame.

Our results show that the formation of the Fe II lines is strongly affected by NLTE effects. For low effective temperatures, $T_{\rm eff} < 20,000\,{\rm K}$, the optical Fe II lines are most influenced by NLTE effects, while for higher $T_{\rm eff}$ the UV lines of Fe II are very strongly affected by NLTE. The departure coefficients are such that Fe II tends to be overionized in NLTE when compared to LTE. Therefore, Fe II-NLTE must be included with sophisticated radiative transfer in nova atmosphere models in order to reliably analyze observed nova spectra. Finally, we show that the number of wavelength points required for the Fe II

NLTE model atmosphere calculations can be reduced from 90,000 to about 30,000 without changing the results if we choose a sufficiently dense UV wavelength grid.

Radiative Transfer in the Co-Moving Frame

with E. Baron and A. Mezzacapa

We discuss the formulation of the radiative transfer equation in the co-moving frame. We show that the time-independent or quasi static approximation is adequate for most astrophysical problems including supernovae. We also discuss the form of mean opacity in the co-moving frame and the use of Eulerian approximations such as Sobolev.

We have shown that advection cannot be neglected in the co-moving solution of the radiation transport equation. Its main effect is on the temperature structure through the term it adds to the equation of radiative equilibrium.

We have also shown that the Sobolev approximation is invalid for weak lines in the co-moving frame, since many of these lines overlap.

We have derived an approximate expression (good to $O(\beta)$) for the Rosseland mean opacity which can be used in radiation hydrodynamical calculations. The important effect of the Doppler shift is fully accounted for in this approximation. We have also derived an accurate and easy to implement approximation to the co-moving frame mean opacity.

List of Publications: 1995
Peter H. Hauschildt

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2: Baron, E., Hauschildt, P.H., Branch, D., Austin, S., Garnavich, P., Ann, Hong Bae, Wagner, R. M., Filippenko, A. V., Matheson, T., Liebert, J.: 1995, *NLTE Spectral Analysis and Model Constraints on Supernova 1993J*, Astrophys. J., **441**, 170–182 **(refereed)**

3: Nugent, P., Baron, E., Hauschildt, P.H., Branch, D.: 1995, *Spectrum Synthesis of the Type Ia SNe 1992A and 19981B*, Astrophys. J. Lett., **441**, L33-36 **(refereed)**

4: Allard, F., Hauschildt, P.H.: 1995, *Model Atmospheres for M (Sub)Dwarfs: I. The base model grid*, Astrophys. J., **445**, 433–450 **(refereed)**

5: Baron, E., Hauschildt, P.H., Young, T. R.: 1995, *Supernova 1993J: One year later*, Phys. Repts., **256**, 33 **(refereed)**

6: Hauschildt, P.H., Starrfield, S., Shore, S. N., Allard, F., Baron, E.: 1995, *The Physics of Early Nova Spectra*, ApJ, **447**, 829 **(refereed)**

7: Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P.H.: 1995, *New evolutionary tracks for very-low-mass stars*, Astrophys. J. Lett., **446**, L35-L38 **(refereed)**

8: S. Pistinner, G. Shaviv, Hauschildt, P.H., S. Starrfield: 1995, *Some Remarks about Nova Spectroscopy and Photometry*, Astrophys. J., **451**, 724-738 **(refereed)**

9: Nugent, P., Branch, D., Baron, E., Fisher, A., Vaughan, T., Hauschildt, P.H.: 1995, *Low Hubble Constant from the Physics of Type Ia Supernovae*, Phys. Rev. Letters, **75**, 394 **(refereed)**

10: Hauschildt, P.H., Baron, E.: 1995, *Non-LTE Treatment of Fe II in Astrophysical Plasmas*, JQSRT, **54**, 987–999 **(refereed)**

11: Jones, H. R. A., Longmore, A. J., Allard, F, Hauschildt, P.H., Miller, S., Tennyson, J.: 1995, *Water vapour in cool dwarf stars*, MNRAS, **277**, 767 **(refereed)**

12: Baron, E., Hauschildt, P.H., Mezzacappa, A.: 1996, *Radiative Transfer in the Co-Moving Frame*, MNRAS, *in press* **(refereed)**

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14: Baron, E., Hauschildt, P.H., Branch, D., Kirshner, R. P., Filippenko, A. V.: 1996, *Preliminary Spectral Analysis of SN 1994I*, MNRAS, *in press* **(refereed)**

15: Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., Hauschildt, P.H.: 1996, *Infrared Spectra of low-mass stars: Towards a temperature scale for red dwarfs*, ApJS, *in press* **(refereed)**

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17: Hauschildt, P.H., Baron, E., Starrfield, S., Allard, F.: 1996, *The Effects of Fe II NLTE on Nova Atmospheres and Spectra*, ApJ, *in press* **(refereed)**

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20: Baron, E., Hauschildt, P.H., Nugent, P., Branch, D.: 1996, *NLTE Effects in Modeling of Supernovae near Maximum Light*, ApJ, *submitted* **(refereed)**

Publications in conference proceedings:

21: Hauschildt, P.H., Starrfield, S., Shore, S. N., Allard, F., Baron, E.: 1995, *The Physics of Early Nova Spectra*, in *Cataclysmic Variables*, A. Bianchini *et al*, Eds., Kluwer Academic Publishers, pp. 257–265.

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